The Sun's role in Climate Changes

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Abstract

For more than a hundred years there have been reports of an apparent connection between solar activity and Earth's climate. Solar activity is now known far back in time due to the production of isotopes in the atmosphere by galactic cosmic rays. From such records there is a striking qualitative agreement between cold and warm climatic periods and low and high solar activity during the last thousand years. Whether the recently measured global warming trend is dominated by anthropogenic effects or has a significant or even dominant solar component is not yet fully understood. In this presentation I will summarize the different ways the Sun can contribute to climate changes. These include the direct forcing from changes in the solar irradiance as well as indirect effects from variations in the UV/EUV flux, causing changes in the dynamics and chemistry of the Earth's atmosphere. The recent proposed link between cosmic rays and cloud production in the lower atmosphere will also be discussed. The climate of the future will be the sum of man-made and natural variations. Thus, it is very important to continue studying the Sun in detail and to monitor the long term variations in solar activity to better understand its possible climate forcing.

1 Introduction

Numerous attempts have been made over the years to link various aspects of solar variability to changes in the Earth's climate. Since the Sun's output of electromagnetic radiation and energetic particles varies, and since the Sun is the ultimate driver for the climate system, it seems natural to link the two together and look for the source of climate variability in the Sun itself. In the mid seventies [3] pointed out the rough coincidence between the cold period of the so-called Little Ice Age in the late 17th and the early 18th centuries and the Maunder Minimum of sunspot activity, when no sunspots were detected for a period of about 45 years. Eddy also used radiocarbon records to show that there was also a rough coincidence between earlier periods of warmth and cold in the northern hemisphere and periods of unusually high and low solar activity respectively. He suggested that the cause might lie in the variations in the Sun's total radiative output (the solar "constant"). In recent years there has been a growing concern about the possible anthropogenic forcing of climate change through the increasing atmospheric content of greenhouse gases. This has made the connection between solar variability and global climate change a very controversial research area. In this short paper I will try to summarize some of the possible mechanisms involved in solar induced climate forcing.

2 Solar variability and climate forcing

There are basicly three ways the Sun could contribute to climate changes.

- A change in the solar total (wavelength-integrated) irradiance.

- A change in ultraviolet irradiance, which modulates the temperature, chemistry, and dynamics in the Earth's atmopshere.
- Direct and indirect influence by solar and cosmic ray particles modulated by the solar wind and the Sun's magnetic field.

2.1 Variations in Total Irradiance

The most obvious candidate for climate forcing is the direct effect of the varying total irradiance with solar activity. For the last two decades it has been possible to make high-precision measurements of the total solar irradiance outside the Earth's atmosphere. The variation with the 11-year cycle is about 0.1%. The effect of this cycle variation has been measured in sea-surface temperatures [15]. However, since the thermal inertia of the ocean will dampen the cycle variation considerably it is long term trends in solar activity we should look for. Despite the lack of direct observations, several attempts have been made to estimate the long term variation in the Sun's radiative output since the Maunder Minimum. The general conclusion of these estimates is that the Sun's total irradiance has probably varied by somewhere between 0.2 and 0.6% over the 300-year period. The value often used in climate models is a 0.25% increase in total irradiance. Based on this value it is often assumed that the Sun may have contributed to most of the warming up to 1940 but only a smaller part (25%) the last few decades.

2.2 Variations in UV Spectral Irradiance

The solar cycle variation at ultraviolet wavelengths are much larger than the 0.1% variation mentioned above. For example the EUV flux derived from SOHO images has increased by a factor 8 over half a solar cycle. Since certain UV wavelengths are responsible for production and loss of ozone in the stratosphere and troposphere any variation in the UV emission from the Sun will produce changes in chemistry and dynamics of the atmosphere. These changes can propagate downward and cause climate variations. An example is a very clear variation of the height of the 30 hPa pressure level in phase with the solar activity variation [9]. This correlation has been constant during the last 4 solar cycles. Recently proxy data have been to derive long term changes in the ultraviolet emission from the Sun [12]. It was found that the UV ($\leq$300nm) wavelengths have increased by 3% since Maunder Minimum that may have produced profound long-term effects in the Earth's atmosphere such as changes in the total amount of ozone. The latter could cause a significant climate forcing.

2.3 Variations in the Solar Wind and the Sun's magnetic flux

Although the energy in the solar wind is negligible compared to the energy in the ultraviolet and visible spectral bands, the relative variations are much larger. From records of the radio-isotopes ^{14}C and ^{10}Be we know there is a clear signal in the troposphere and ground. But how can these small energy fluctuations possibly affect the climate? The cosmic ray flux is the main cause of ionization of the upper atmosphere and this ionization changes significantly with solar activity. Recently it has been suggested that cosmic rays may play a role in cloud formation. The effects of ionization or electric fields associated with solar activity on the freezing of supercooled water droplets in high clouds have also been studied [14]. Another process related to cloud formation has recently been presented [13] [10]. It was found that the global cloud cover measured by satellites during a considerable part of a solar cycle was highly correlated with the cosmic ray flux. Using an improved and recently released data set from International Cloud Climate Project (ISCCP) covering a period from 1983 to 1994 it was demonstrated that only the low clouds are responsible for the found correlation. This is very important information because it gives a much better hint regarding the microphysical processes that may be involved.

The cosmic ray cloud connection has been criticized by others and it has been argued that there are no known mechanisms that could explain this effect. However, recent computer simulations of aerosol formation by ion-ion recombination have been presented [16]. These results shows indeed that ionization by cosmic rays may enhance cloud condensation, in particular at low altitudes. Much more work needs to be done before we understand these possible mechanisms. To test the coupling between high energy particles and clouds an experiment at CERN has been proposed. Hopefully the CLOUD experiment will be funded in the near future (for more information see: http://cloud.web.cern.ch/cloud/).

A change in cloud cover would indeed be a very effective amplifying mechanism for climate forcing. The pattern of systematic change in the global climate over recorded history seems to follow the observed changes in cosmic-ray flux, and it is consistent with the explanation that a low cosmic-ray flux corresponds to fewer clouds and a warmer climate, and vice versa. There has been a systematic decrease in the cosmic-ray flux by about 15% over the course of the last century, caused by a doubling of the solar coronal-source magnetic flux.

There are further evidences that variations in the cloud cover may be driven by the solar activity. The Earth's atmosphere is not alone in displaying variable properties related to the solar cycle. The brightness of Neptune appears to displays an influence possibly related to solar activity [7]. Neptune's clouds consist mostly of frozen methane, so the planet is quite shiny and reflects a large fraction of the solar radiation. Since 1973 observations have shown that the de-trended brightness of the planet is varying by 3-4% and is in phase with the solar cycle. Neptune is brightest at sunspot minimum, which is at cosmic ray maximum. Thus, Neptune's cloud properties appear to be linked to the cosmic ray flux, similar to the situation for terrestrial clouds. This opens the possibility that a link between solar activity and planetary atmospheres is a general feature of our solar system.

Recently measurements of the Earth's albedo have been presented [4]. By measuring "Earth-shine" reflected off the dark side of the moon, the Earth's albedo (i.e. Earth's ability to reflect sunlight) can be determined. They found a 2.5% decrease in Earth's albedo over the past 5 years, a variation of the same order as measured by satellites during the last solar cycle. Forthermore, evidence for a statistically strong relationship between cosmic ray flux and precipitation and precipitation efficiency over ocean surface at mid to high latitudes has been reported [6].

Another interesting result comes from a study of planktonic foraminifera from extracted cores in the Mediterranean [2]. An 11 year variability is identified and is in phase with the solar activity cycle. The secular increase however, between 1760 and 1950 was found to be 3.7 times higher than the 11 year signal. This amount appears to be bigger than can be explained by changes in the solar irradiance itself. Thus, a considerable reduction in the cloud cover could explain this large increase.

Two papers published during the same week, in Science and in Nature, present convincing evidence that the Sun is the main driver of climate change on a decadal-to-century timescale. The relationship between a ^{14}C tree-ring record and a δ^{18}O proxy record of monsoon rainfall intensity as recorded in calcite δ^{18}O data obtained from a stalagmite in northern Oman for the period 9,600-6,100 years ago was studied [11]. An "extremely strong" relationship between the two data sets was reported. Comparison of lake sediment core data taken from Mexico's Yucatan Peninsula and a ^{14}C tree-ring record covering the past 2600 years revealed similar periodicities [5]. It was concluded that "a significant component of century-scale variability in Yucatan droughts is explained by solar forcing."

With respect to more recent solar and climatic history it was shown that, contemporaneously with the warming of the earth, the sun's total magnetic flux rose by a factor of 1.41 over the period 1964-1996 and by a factor of 2.3 since 1901 [8].

3 Summary

Whether the global warming trend recently measured is dominated by anthropogenic effects or has a significant or even dominant solar component is not yet fully understood. The climate of the future will be the sum of man-made and natural variations, but the man-made part cannot be estimated reliably until the contributions of natural agents (Sun, volcanoes, El Nino) have been defined, and subtracted from the observed changes of the past 100 years.

Most of the current climate models only include the direct solar forcing from changes in the total irradiance. A simple climate model that compared the forcing from the changes in solar irradiance with changes in both irradiance and solar induced cloud cover has been tested [1]. If one assume that the cosmic ray cloud interaction has been present the last 150 years the forcing from clouds and irradiance changes can explain most of the increase in global surface temperature. However, much work needs to be done on this topic and we need to monitor both the Sun and atmospheric parameters such as clouds, ozon, circulation patters etc. over several solar cycles to better understand the apparently complex amplifying mechanisms that takes place.

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